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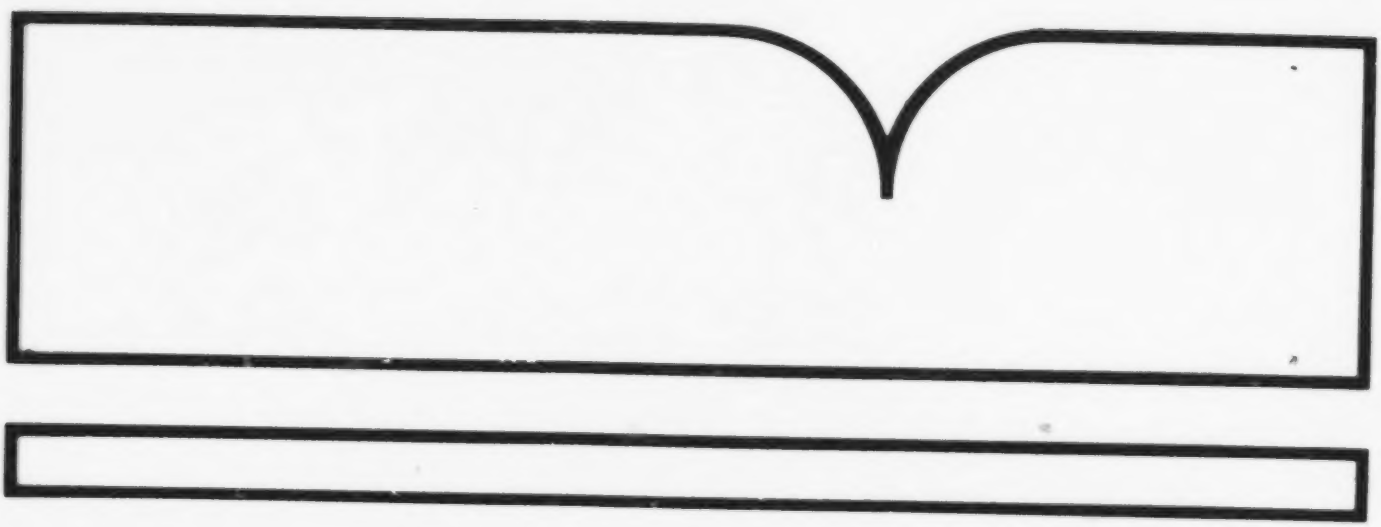

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INFLUENCE OF COAL COMPOSITION ON THE FATE OF VOLATILE AND CHAR NITROGEN DURING COMBUSTION

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16. ABSTRACT The paper gives results of burning 50 coals from North America, Europe, Asia, South Africa, and Australia in a 21 kWt refactory-lined tunnel furnace to determine the influence of coal properties on the fate of volatile and char nitrogen. Excess-air fuel NO emissions (determined by combustion in Ar/O2/CO2) ranged from 415 to 1380 ppm with a premixed burner. These results correlated with total fuel nitrogen, inert pyrolysis HCN yield, and non-volatile nitrogen content, rather than with the geographic origin of the coal. Minimum staged NO emissions (at optimum first stage stoichiometry) ranged from 140 to 380 ppm. Detailed in-flame measurements indicated that, as first stage stoichiometry (air/fuel) was reduced, first stage NO formation decreased, but was ultimately offset by increases in oxidizable gaseous nitrogen species and solid phase nitrogen retention. TFN (NH3 + NO + HCN) generally increased with increasing fuel nitrogen, and the species distribution depended on coal rank. In general, HCN was greater than NH3 with bituminous coals, but less than NH3 with subbituminous and lignite coals. Second stage TFN conversion to exhaust NO decreased as the TFN distribution was shifted in favor of HCN and NH3. Char nitrogen conversion was generally low (less than 20%).

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Combustion	Stationary Sources	21B
Coal	Composition	21D,08G
Chemical Analysis	Volatile Nitrogen	07D
Nitrogen	Char Nitrogen	07B
Volatility		20M
Charring		

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ABSTRACT

Fifty coals from North America, Europe, Asia, South Africa, and Australia were burned in a 21 kW_t refractory-lined tunnel furnace to determine the influence of coal properties on the fate of volatile and char nitrogen. Excess-air fuel NO emissions (as determined by combustion in $Ar/O_2/CO_2$) ranged from 415 to 1380 ppm with a premixed burner. These results correlated with total fuel nitrogen, inert pyrolysis HCN yield, and non-volatile nitrogen content, rather than with the geographic origin of the coal.

Minimum staged NO emissions (at optimum first stage stoichiometry) ranged from 140 to 380 ppm. Detailed in-flame measurements indicated that as first stage stoichiometry (air/fuel) was reduced, first stage NO formation decreased, but was ultimately offset by increases in oxidizable gaseous nitrogen species and solid phase nitrogen retention. TFN (NH_3 + NO + HCN) generally increased with increasing fuel nitrogen, and the species distribution was dependent upon coal rank. In general, HCN was greater than NH_3 with bituminous coals, but less than NH_3 with subbituminous and lignite coals. Second stage TFN conversion to exhaust NO decreased as the TFN distribution was shifted in favor of HCN and NH_3. Char nitrogen conversion was generally low (less than 20 %). Exhaust emissions were correlated in terms of the gas phase TFN and the char nitrogen entering the second stage.

Increasing heat extraction generally reduced exhaust NO emissions via a complex mechanism. Reducing second stage flame temperatures had little effect on the concentration and speciation of the XN species leaving the first stage, and on the conversion of solid phase nitrogen. However, it dramatically decreased the conversion of gas phase TFN to exhaust NO. The controlling

mechanism appears to be selective NO reduction by NH_i species. The effectiveness of increased heat extraction rate was also found to depend heavily on the coal composition.

INTRODUCTION

Conventional, coal-fired power plants may remain the major source of electricity world wide for decades due to uncertain oil supplies and concern over nuclear generating plants. Many countries without adequate domestic supplies are importing coal from North America, Australia, South Africa, and Eastern Europe. Operational expertise with these coals is limited because they represent newly exploited reserves. Additionally, individual power plants may be required to burn a variety of coals due to supply limitations. Consequently, predicting the combustion and pollutant performance of a coal based on comparative laboratory analysis and bench scale tests with a limited sample is important. This paper summarizes a methodology whereby coals can be ranked according to their nitric oxide (NO) production potential.

The development of NO control strategies for coal-fired boilers has received considerable attention over the past decade. Pilot-scale studies[1] established that fuel/air mixing controlled by burner design dictated the formation of NO in pulverized coal flames and that rapid mixing of coal volatiles and air promoted NO formation. Bench-scale and research studies further established the significance of fuel nitrogen oxidation[2], the factors controlling fuel nitrogen evolution[3,4], and conditions that affect NO formation from pulverized coal under fuel-rich conditions[5,6]. Burner designs have been demonstrated at various scales[7,8,9], which are capable of minimizing emissions from field-operating boilers, and more advanced combustion control techniques have been proposed which will substantially change state-of-the-art boiler designs[10]. However, little information is currently available regarding fuel property effects on these low emissions concepts.

Pulverized coal combustion produces nitric oxide by the fixation of molecular nitrogen (thermal NO) and by the oxidation of coal bound nitrogen (fuel NO). Thermal NO formation is extremely temperature dependent; however, flame temperature has only a minor effect on fuel NO formation. The key parameter controlling fuel NO formation from a given coal is gas-phase reactant stoichiometry. Excess oxygen promotes fuel NO formation. Since fuel nitrogen oxidation is the primary NO formation mechanism, the fate of coal nitrogen must be defined to establish the NO emissions potential of different coals.

When a pulverized coal particle is injected into a flame, it decomposes and the fuel-bound nitrogen splits between the char and the volatile fractions. The volatiles are composed of tars and light gases, and the tars further decompose after ejection from the coal particle, producing gas-phase nitrogen compounds and soot. Char nitrogen is defined as that which is associated with a solid, either as a pyrolysis product of the tars or as the original coal char; gas-phase volatile nitrogen is that which is produced from the volatile coal fractions and reacts in the gas phase forming N_2, NO, HCN, or NH_3.

This study assessed the impact of coal properties on the fate of both char and volatile (fuel-bound) nitrogen under excess-air and fuel-rich (staged) combustion conditions. A total of 48 coals from 5 continents were burned in a 21 kW_t refractory-lined tunnel furnace using air and nitrogen-free mixtures as the oxidant. Exhaust and in-flame measurements were made to quantify the influence of coal properties, thermal environment, and stoichiometry on the amount and speciation of volatile and char nitrogen at the exit of the first stage and on the conversion of the fuel nitrogen fragments in the second stage.

EXPERIMENTAL

A complete description of the experimental system and the analytical techniques used in this study is available elsewhere[11], and only a brief summary will be presented below.

Furnace System

The investigations were carried out in a 15.2 cm diameter by 2 m long, vertical refractory-lined reactor which consisted of five separate sections and was fired at a rate of 21 kW_t (approximately 2.6 kg/hr coal). The furnace entry diverged from 5.1 cm to the full 15.2 cm diameter in 30.5 cm.

Pulverized coal was supplied pneumatically from a hopper-fed screw feeder to the premixed burner. Premixing was achieved by direct impingement of the coal jets with the main combustion air supply in a premixing chamber. This chamber was separated from the combustion zone by a series of water-cooled tubes which prevented flashback. The coal/air mixture burned in a plug-flow mode with the ignition zone situated in the divergent entry section.

During the staging experiments a refractory choke was inserted to isolate the fuel-rich first stage from the second (burnout) stage. Second stage air was injected radially, immediately after the choke, through a ring.

Analytical Methods

Exhaust samples were withdrawn from the reactor stack with a stainless steel, water-jacketed probe and analyzed using standard continuous instrumentation (chemiluminescent NO, paramagnetic O_2, and NDIR CO and CO_2). A water-jacketed probe with an internal water-quench spray near the front end was used for extracting in-flame samples[11]. Gas phase HCN and NH_3 species were collected in a gas washing unit which consisted of an impinger in series with a bubbler containing a fritted glass cylinder. The sample

solutions were subsequently analyzed for CN^- and dissolved ammonia using specific ion electrodes. A solution of lead carbonate and sodium carbonate was used in both the impinger and the bubbler to remove sulfide ions. The probe and analysis systems were validated by sampling gases of known composition.

Solid samples were withdrawn isokinetically from the combustion zone with a water-spray probe. Their ultimate composition was determined with a Perkin-Elmer 240 B Elemental Analyzer.

Fuels

Table 1 gives composition information on the 48 coals used in this study. They ranged from anthracite through lignite and were all pulverized so that 65 ± 7% of the mass passed through a 200 mesh (74 μm) screen.

OVERALL RESULTS

Figure 1 shows fuel NO emissions (excess air) from the 48 coals and the minimum NO (staged) as a function of the coal nitrogen (dry, ash free). (Open symbols represent American coals.) Fuel NO was defined by burning each coal in a nitrogen free oxidant ($Ar/O_2/CO_2$)[11], and air was used as the oxidant in the staged combustion experiments. In both instances, the overall excess oxygen was 5%.

Excess Air

Fuel NO emissions generally increased with increasing fuel nitrogen content. The geographic source of coal had little impact upon fuel NO production; non-U.S. coals behaved similarly to U.S. coals. The highest nitrogen coal tested was Russian (✚) (2.46% N daf) which also gave the highest NO emissions. Low rank coals usually contained less nitrogen and produced less fuel NO than high volatile bituminous coals. The North Dakota lignites (□,◇) contained less than 1.12% nitrogen and gave very low emissions. However, within any rank, properties other than total fuel nitrogen influenced fuel NO. For example, the Savage (△) and Beulah (□) lignites both contained approximately 1.05% nitrogen, yet their emissions differed by more than 60%. Lowest overall emissions were from Pennsylvania anthracite (▱); highest (relative) emissions were from North Carolina peat (◈). The anthracite contained virtually no volatile nitrogen, whereas the peat nitrogen was all highly volatile. These results suggested that fuel NO formation is highest with fuels which evolve the most reactive volatile nitrogen and lowest when the nitrogen is retained in the solid phase until the char burnout regime.

In an attempt to quantify these effects, Solomon and co-workers[12] determined the reactive volatile nitrogen content of the 19 most diverse coals by pyrolyzing them in vacuum of 1370 K and measuring the HCN yield by FTIR. The tendency of each coal to retain nitrogen in the solid phase was characterized by conducting a standard ASTM proximate analysis and subsequently measuring the nitrogen content of the residual char. These results are contained in Table 1, and a multi-variable regression algorithm yielded Equation (1).

$$NO = 318 + 702\,[N] + 0.188\,[HCN] - 0.347\,[\text{non-volatile N}] \qquad (1)$$

where,

[N] = wt. % nitrogen in original coal (daf)

[HCN] = inert pyrolysis HCN yield, ppm equivalent

[non-volatile N] = modified ASTM solid nitrogen, ppm equivalent.

Figure 2 compares the results of the empirical correlation with the experimental measurements. The high correlation coefficient ($r^2 = 0.9$) was encouraging because the fuels tested ranged from the 2.5% nitrogen, high volatile Russian bituminous coal to the 0.68% nitrogen, pre-dried Australian brown coal and included the anthracite. The actual numerical constants in the equation are unimportant; they are clearly a function of the burner system and the time/temperature profile within the furnace. However, the form of the correlation is consistent with the physical understanding. The first two terms represent the mean behavior with respect to total nitrogen content and reflect the decreasing fuel nitrogen conversion with increasing fuel nitrogen (conversion to NO proportional to $[N]^{-1}$). Additionally, coals which have high volatile nitrogen yields have increased emissions, and those which retain significant nitrogen in the solid phase, give emissions slightly

below the mean behavior.

Staged Combustion

Figure 1 also shows the minimum NO emissions achieved under staged conditions. (All minimums were not achieved at the same first-stage stoichiometry.) In general minimum NO emissions increased with increasing nitrogen content and again depended on factors other than total nitrogen. These data do not correlate directly with volatile and char nitrogen because the controlling processes are extremely complex as discussed later.

INFLUENCE OF FUEL PROPERTIES ON STAGED COMBUSTION EFFECTIVENESS

First Stage Process

Staged combustion minimizes NO emissions because the initial fuel-rich conditions promote the formation of N_2 from volatile nitrogen species. Exhaust NO levels depend upon the conversion and level of the reduced nitrogen species and char nitrogen which exit the first stage, and experiments were conducted to quantify the relationships between nitrogen species and coal type. The second stage air was added 1.2 m from the burner, and the first stage stoichiometry (SR_1) (moles O_2 supplied/moles O_2 required for complete combustion) was varied while maintaining excess oxygen at 5%.

Figure 3 shows typical results for bituminous and lignite coals. As SR_1 was reduced, the exhaust NO decreased, reached a minimum, and then increased. The primary-zone stoichiometry at the minimum exhaust NO and the NO/SR_1 gradient were dependent upon coal characteristics. No minimum in exhaust NO was observed with anthracite or gasification chars. Char-nitrogen concentrations increased with decreasing primary zone stoichiometry. The major gas-phase nitrogen species were NO, NH_3, and HCN (collectively termed TFN); lower levels of N_2O were also observed[13]. Decreasing SR_1 decreased the NO exiting the first stage, but ultimately increased other TFN species. This behavior is analogous to that reported previously for gas and liquid fuel flames[14,15]. In general, the TFN exiting the first stage increased with increasing coal nitrogen content, but TFN did not correlate with inert pyrolysis HCN yield.

Figure 3 also indicates that gas-phase nitrogen speciation depends on coal rank. Figure 4 summarizes the partition of TFN as a function of rank at the first stage exit. The fraction of coal nitrogen converted to NH_3

increased with decreasing rank. First stage NO exhibited the reverse trend; decreasing rank decreased NO. In general, HCN concentrations were small. Only the Utah bituminous coal (O) produced a significant amount of HCN at SR_1 = 0.6. The differences in TFN partition with decreasing rank can be attributed (1) to variations in hydrocarbon volatiles which control local O_2 availability and provide a path for CN and ultimately NH_i formation from NO[16], and (2) to increased volatile nitrogen yields which ultimately result in increased NH_i concentrations.

Second Stage Processes

The second stage of a staged-combustion system is analogous to an excess-air flame burning partial-oxidation products produced in the first stage. The ultimate NO yield depends upon the TFN and char nitrogen conversion. Figure 5 presents results obtained to assess the conversion of gaseous and char nitrogen species to NO in the second stage flame. Tests were conducted (Figure 5a) with C_3H_8/NH_3 and C_3H_8/NO flames in the first stage (no solid-phase present, first stage residence time = 1.0 sec @ SR_1 = 0.6, 1.41 wt % N in fuel, 21 kW_t). The percent TFN conversion in the second stage was computed based upon detailed species measurements at the first stage exit and in the exhaust. When NO was the dominant TFN species (SR_1 > 0.75), the second stage conversion (retention) of TFN to NO was very high (approximately 90%) and relatively insensitive to total TFN level. Under these conditions, only limited heat release in the second stage occurred and the second stage "fuel" was primarily CO. As SR_1 was reduced further and the dominant TFN species became NH_3 and HCN, the second stage conversion decreased dramatically and was inversely dependent on the TFN level. Figure 5a also shows data on second stage TFN conversions in char/C_3H_8/NH_3 flames. Similar trends were observed; the solid phase had relatively little effect on TFN conversion in

the second stage.

Second stage char nitrogen conversion to NO was defined by burning COED char/C_3H_8 in a nitrogen free oxidant. This system provided a second stage reactant stream with minimal TFN species. Figure 5b shows the calculated conversion data based on the TFN and exhaust NO. (The error bars are uncertainty due to limited TFN conversion.) Char nitrogen conversion to NO in the second stage was 20% or less and increased slightly with decreasing SR_1. A multi-variable non-linear regression was used to calculate exhaust NO concentrations with the amount and speciation of the TFN and char nitrogen entering the second stage. The resulting correlation was:

$$NO_{EX} = 0.87*SR*(NO) + \frac{0.67}{1+0.004(HCN+NH_3)}(HCN+NH_3) + 0.27\ (1-SR)^{\frac{1}{2}}(\text{Char N}) \quad (2)$$

and the overall correlation coefficient (r^2) was 0.9 based on 26 data sets.

Practical Implications

Minimum exhaust NO data (Figure 1) emphasized the importance of coal characteristics: the Norway (▲) and Alabama (Ω) bituminous coals both contain approximately 1.85% N (DAF) but their minimum NO emissions differed by 45%. The previous discussions have indicated that coal properties influence staged combustion effectiveness by altering:

- The partition of nitrogen between the volatile and char phases. Nitrogen remaining in the char during the first, fuel rich, stage reduces the TFN available for N_2 formation. Since char nitrogen conversion is non-negligible, as the TFN tends to zero, it sets a limit on minimum achievable exhaust NO.
- Gas Phase Speciation. Second stage processing of TFN is species dependent: high levels of NO are undesirable because a large fraction is retained through the second stage flame.

Figure 6 summarizes the relative contribution of each nitrogen component (leaving the first-stage) to exhaust NO emissions. These results were derived by using the correlation (Equation 2) and the internal measurements for the Alabama and Norway coals. Norway coal has a lower minimum NO because the first-stage NO is low due to high volatile-hydrocarbon evolution and because less char nitrogen is available in the second stage. At SR_1 = 0.6, char nitrogen produced 200 ppm NO with Alabama coal and 115 ppm with Norway coal. Thus, staged combustion technologies will be least effective with coals which strongly retain their nitrogen in the solid phase.

ROLE OF THERMAL ENVIRONMENT

Controlling Mechanisms

Increasing primary zone temperature should reduce exhaust NO because it:

- Accelerates the rate of TFN decay, and
- Reduces the amount of char nitrogen.

However, unlike liquid fuels[15] when heat is extracted from the primary zone of a staged coal flame, exhaust emissions decrease rather than increase (Figure 7). These data are in agreement with the observations of Johnson, et al.[10] The detailed internal measurements shown in Figure 7 indicate that decreasing the first stage exit temperature ca. 200 K (by inserting a water cooling coil in the first stage) had little effect on the amount and speciation of the TFN or char nitrogen. Additional studies with COED char/C_3H_8 flames burning in Ar/O_2 indicated that heat extraction rate also had little effect on the oxidation of solid nitrogen in the second stage flame. Therefore, reducing the second stage flame temperature must have decreased TFN conversion.

Figure 8 shows the results of an experimental series where NO or NH_3 was injected into the second stage flame (with the staging air) to define the influence of cooling on second stage TFN conversion. When the added fuel N was NO (○), thermal environment had essentially no effect on the conversion (retention) in the second stage flame; however, when NH_3 was added (△), cooling significantly decreased TFN conversion. Thus, the reduction in exhaust NO emissions with increased heat extraction appears to be due to the reduction of NO by NH_i in the second stage flame. The composition and thermal conditions (cooled = 1150 K at the second stage inlet) are essentially analogous to those defined by Lyon[17] for external "De-NO_x."

Coupling with Fuel Chemistry

Figure 9 shows the influence of heat extraction rate on the Canadian lignite coal. These data (typical of low rank coals) show that increasing heat extraction only reduced exhaust NO at high stoichiometries ($SR_1 > 0.7$). Figure 9 also presents detailed in-flame measurements. Increased cooling had little effect on TFN; however, at rich conditions ($SR_1 < 0.7$), it increased the carry-over of solid nitrogen. Thus, decreased emission associated with a reduced gas phase conversion was somewhat mitigated by an increased contribution from char nitrogen. Figue 10 shows typical results for a high volatile bituminous coal. At high stoichiometric ratios ($SR_1 > 0.7$) reducing first stage temperature increased first stage NO. Thus, there was essentially no effect of decreasing temperature on exhaust NO at $SR_1 > 0.7$ because of a decrease in the first stage NO decay rate and the low NH_3 concentrations.

CONCLUSIONS

The results of this investigation with 50 coals from 5 continents indicate that rank and nitrogen content are more significant than geographic origin of the coal. Excess-air fuel-NO emissions varied from 415 ppm (0.84% N anthracite) to 1380 ppm (2.46% N HVA bituminous) and correlate with total fuel nitrogen, inert pyrolysis HCN yield, and non-volatile nitrogen content.

Minimum staged NO emissions ranged from 140 ppm (0.68% N brown coal) to 380 ppm (1.88% N MV bituminous). As first stage stoichiometry is reduced, first stage NO formation decreases, but other oxidizable gaseous nitrogen species increase as does solid phase nitrogen retention. TFN ($NO + NH_3 + HCN$) generally increases with increasing fuel nitrogen.

The distribution of TFN species depends heavily on coal composition. Low volatile fuels form essentially no NH_3 or HCN. First stage NO percentage decreases signficantly with decreasing coal rank from bituminous to lignite. Conversely, the relative importance of NH_3 grows with decreasing coal rank. In general, HCN is greater than NH_3 with bituminous coals, but less than NH_3 with subbituminous and lignite coals.

Second stage TFN conversion decreases as the TFN distribution shifts in favor of HCN and NH_3 (and as the hydrocarbon content of the second stage reactants increases[11]). Second stage char nitrogen conversion to NO is low (less than 20%) and inversely proportional to SR_1. Exhaust emissions can be correlated with gas phase TFN and char nitrogen.

Increasing heat extraction generally reduces exhaust NO by dramatically decreasing gas phase TFN conversion to NO. If the second stage reactants are cooled to approximately 1150 K, it is possible to enhance the reduction of NO (probably by NH_i species) in the second stage flame. However, the concept's

effectiveness depends on the combustor design and fuel chemistry. Increasing heat extraction appears most favorable with low rank coals, because they produce large amounts of NH_3 and relatively less first stage NO. It should be noted that heat extraction from the primary zone can introduce practical problems because of reduced carbon burnout.

NOMENCLATURE

Char N	Nitrogen remaining in the solid at any point in the combustion process , usually the first stage (rich zone) exit.
daf	dry, ash free
Fuel NO	NO formed from fuel nitrogen as defined by $Ar/O_2/CO_2$ replacement experiments
Non-volatile N	Nitrogen remaining in the solid phase after the ASTM proximate (volatile) determination at 1373 K.
Stoichiometric Ratio	Moles of O_2 supplied/moles O_2 required for complete combustion
SR_1	Stoichiometric ratio in the first (fuel rich) stage
TFN	Total fixed nitrogen species ($NO + NH_3 + HCN$) (gas phase)
Thermal NO	Difference between emissions with air (total NO) and emissions with $Ar/O_2/CO_2$
XN	A reactive, gas-phase, nitrogeneous species (e.g., HCN, NH_i)

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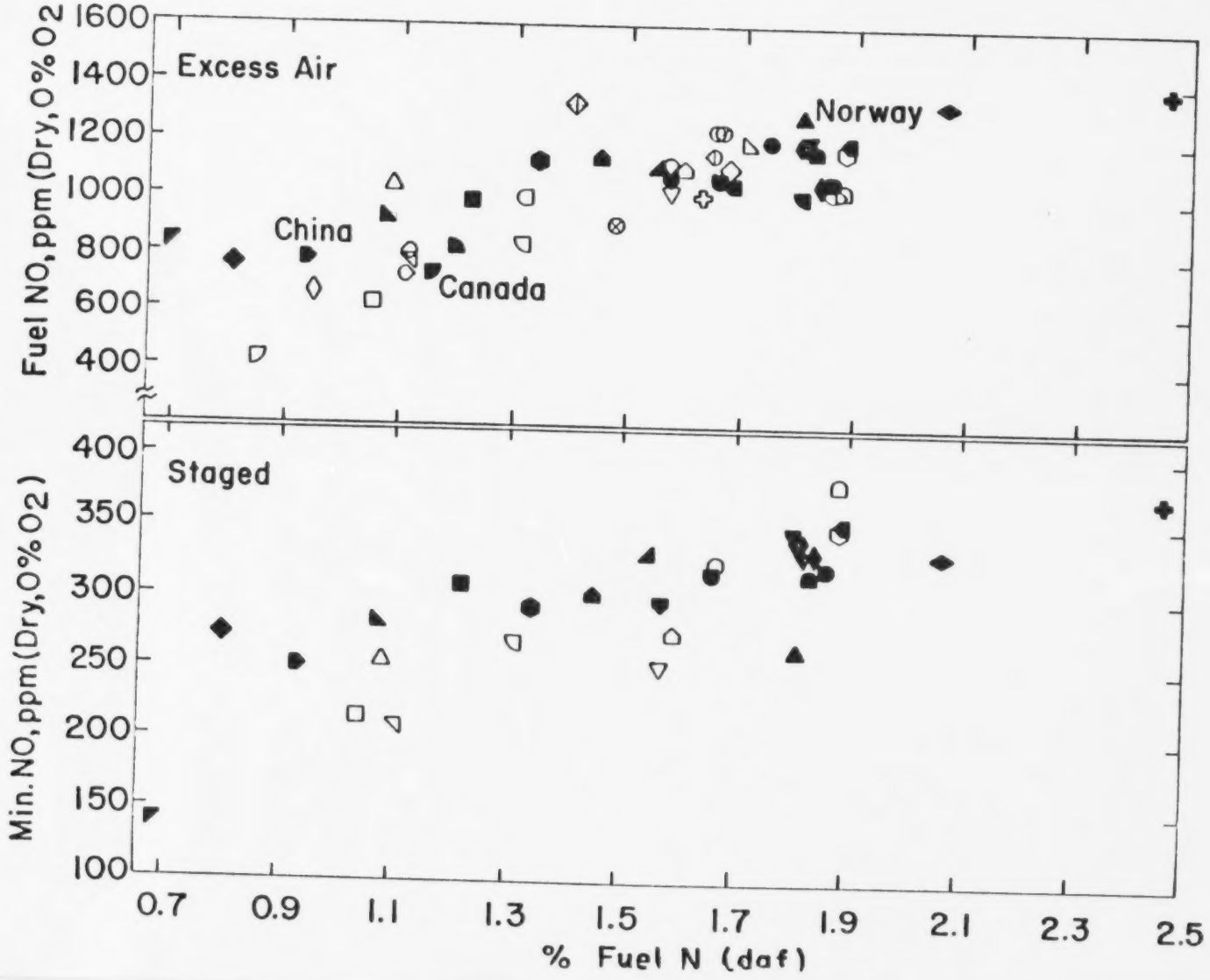
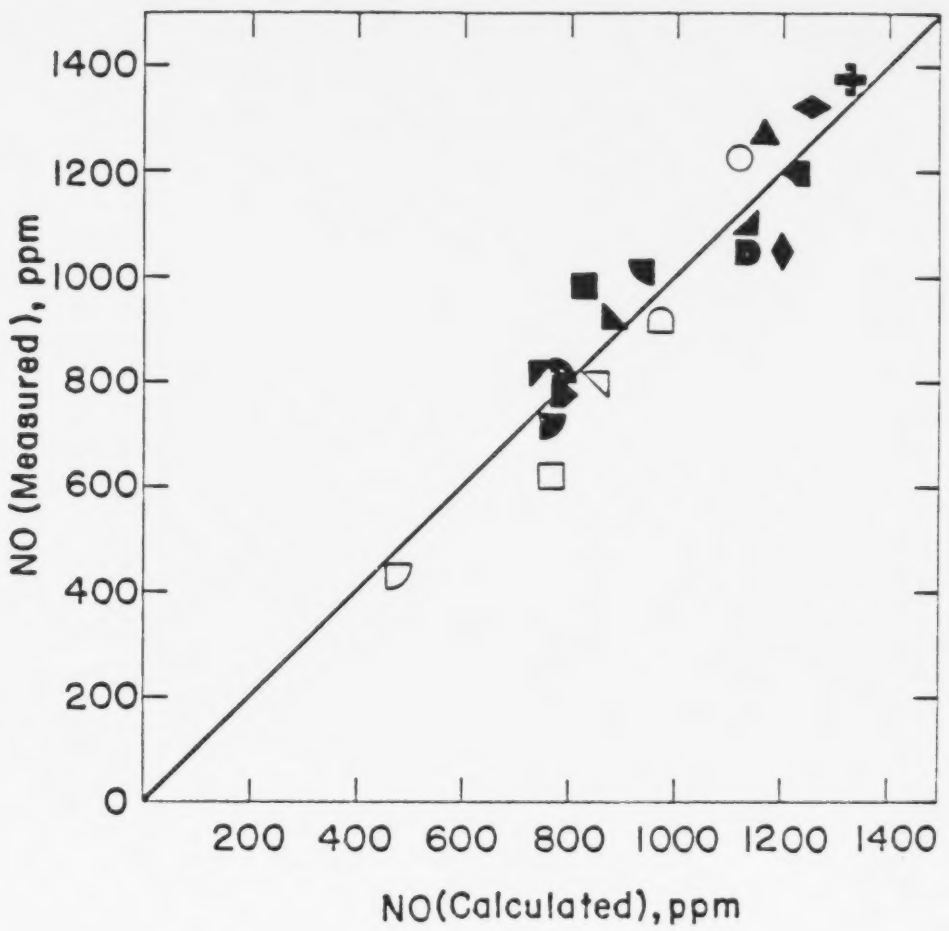
TABLE 1. FUEL ANALYSIS

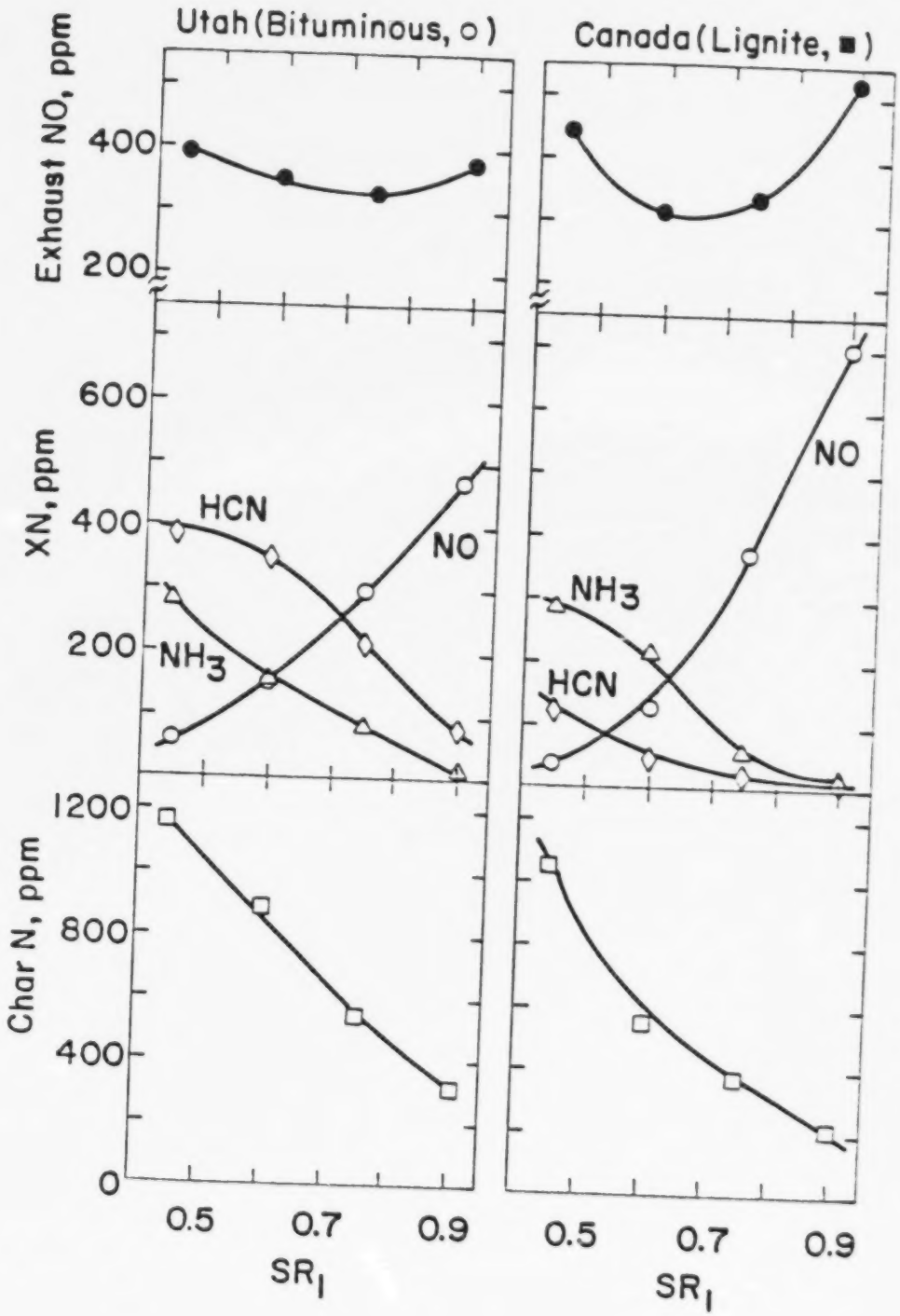
Symbol	Source	Rank (ASTM-D388)	HHV Btu/lb (as received)*	Volatile Matter (daf)	% N (daf)	Pyrolysis HCN ppm Equiv.	Modified ASTM Solid N ppm Equiv.
⊗	Utah Char		11,185	12.79	1.48		
⊠	Coed Char		12,105	9.35	1.95		
▽	Hazellon PA.	A	13,124	4.93	0.84	43	1267
◆	Upper Cliff AL.	MVB	13,254	23.36	1.63		
□	Rosa Alabama	MVB	13,394	25.60	1.88	642	2272
⬡	Black Creek AL.	MVB	14,284	30.31	1.88		
◇	W. KY.	HVAB	12,082	43.42	1.68		
△	W. VA.	HVAB	12,228	36.23	1.59		
◇	Elkay W. VA.	HVAB	13,115	37.99	1.57		
○	Gauley Eagle W. VA	HVAB	10,110	38.41	1.87		
○	Price UT.	HVBB	10,340	45.11	1.67	1267	1762
▷	Price UT.	HVBB	11,877	46.37	1.71		
⊘	Utah	HVBB	11,710	50.14	1.67		
□	Cadiz OH.	HVBB	11,038	55.10	1.32		
⊕	Four Corners, NM.	HVCB	9,425	50.83	1.65		
▽	Colstrip, MT.	SBB	9,169	44.57	1.57		
○	Hardin, MT.	SBB	8,603	47.25	1.11		
◁	Hardin, MT.	SBB	9,339	46.89	1.11	770	1107
◫	TX	SBC	8,131	54.75	1.31		
◇	Scranton, ND.	LA	6,446	50.14	0.94		
○	Beulah, ND.	LA	7,245	47.93	1.11		
□	Beulah, ND.	LA	7,245	44.74	1.04	520	1084
▷	Savage, MT.	LA	6,995	48.25	1.08		
⊕	N C Peat	LA	7,703	63.76	1.40		
◤	Morwell Australia		10,051	55.73	0.68	752	556
◥	Australia	MVB	11,875	30.57	1.81	823	2302
◀	Australia	HVAB	12,683	36.44	1.89	1148	1788
◆	Australia	HVAB	12,005	36.40	2.07	742	1878
◆	Canada	LA	6,107	50.65	0.80		
■	Canada	SBC	7,488	46.78	1.22	434	1221
◢	Canada	SBB	8,356	45.86	1.55	919	1268
◣	Canada	HVCB	10,811	40.78	1.07	675	918
⬢	Blended/US Canada	HVBB	11,882	40.32	1.34		
●	Canada	HVAB	11,862	37.62	1.75		
⬢	Canada	HVAB	14,000	36.99	1.81		
◤	Canada	MVB	11,839	24.04	1.15	448	1276
◣	Canada	MVB	12,920	24.30	1.19	540	1357
▲	Poland	HVBB	10,995	37.93			
✚	Russia	HVAB	11,597	35.60	2.46	740	2322
▶	Australia	HVBB	11,888	33.41	1.86	874	1895
▲	Australia	MVB	11,938	30.60	1.83		
■	Australia	MVB	11,661	32.18	1.66		
▼	S. Africa	HVBB	11,394	36.59	1.57		
▶	China	HVBB	12,005	32.49	0.93	564	856
▲	Norway	HVAB	13,948	41.77	1.81	614	1543
▼	England	HVBB	11,719	33.57	1.81		
◀	W. Germany	MVB	12,622	28.97	1.69		
◆	Australia	HVAB	11,725	34.15	1.84	921	1668

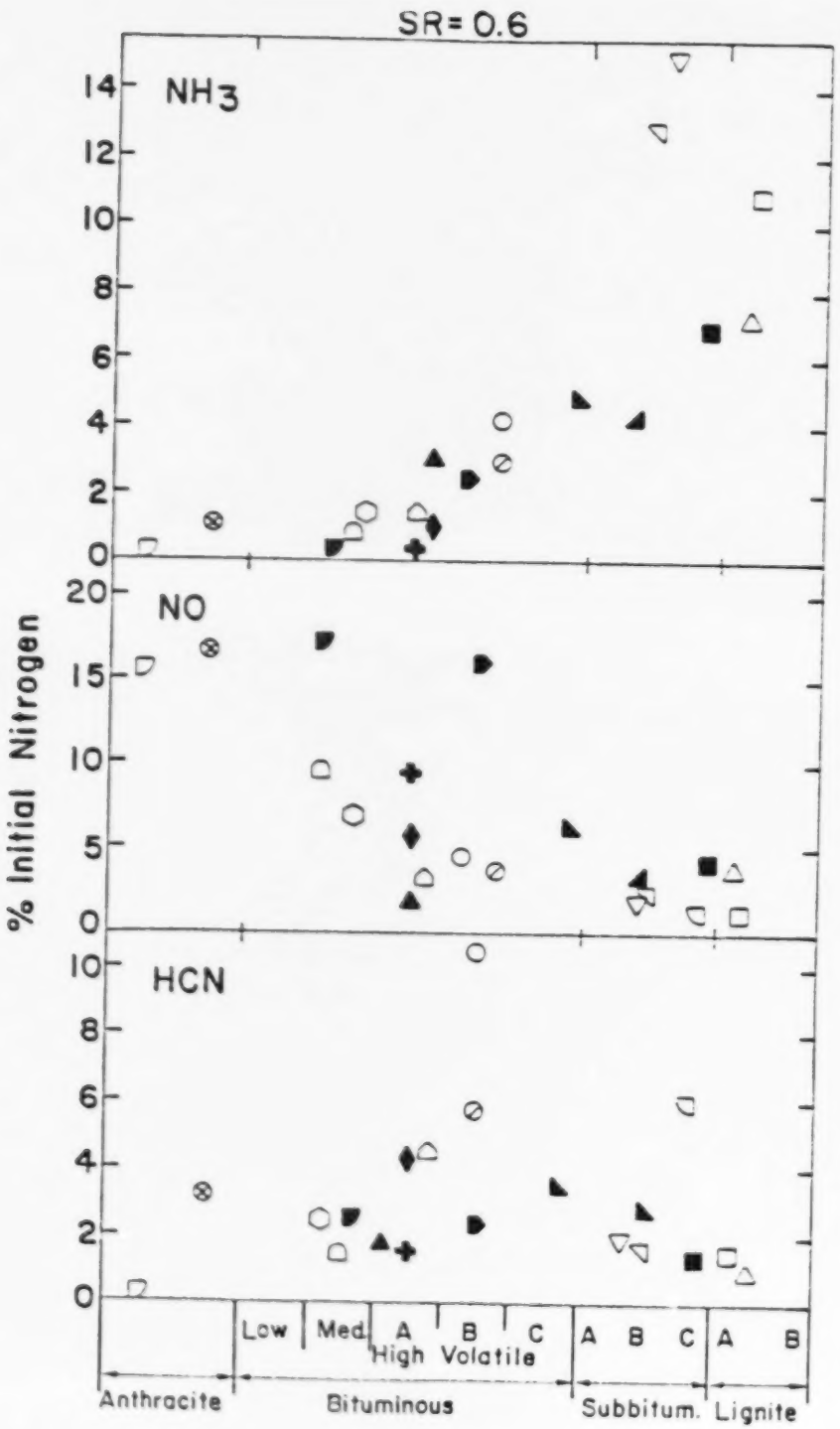
*1 Btu/lb = 2.32 J/g

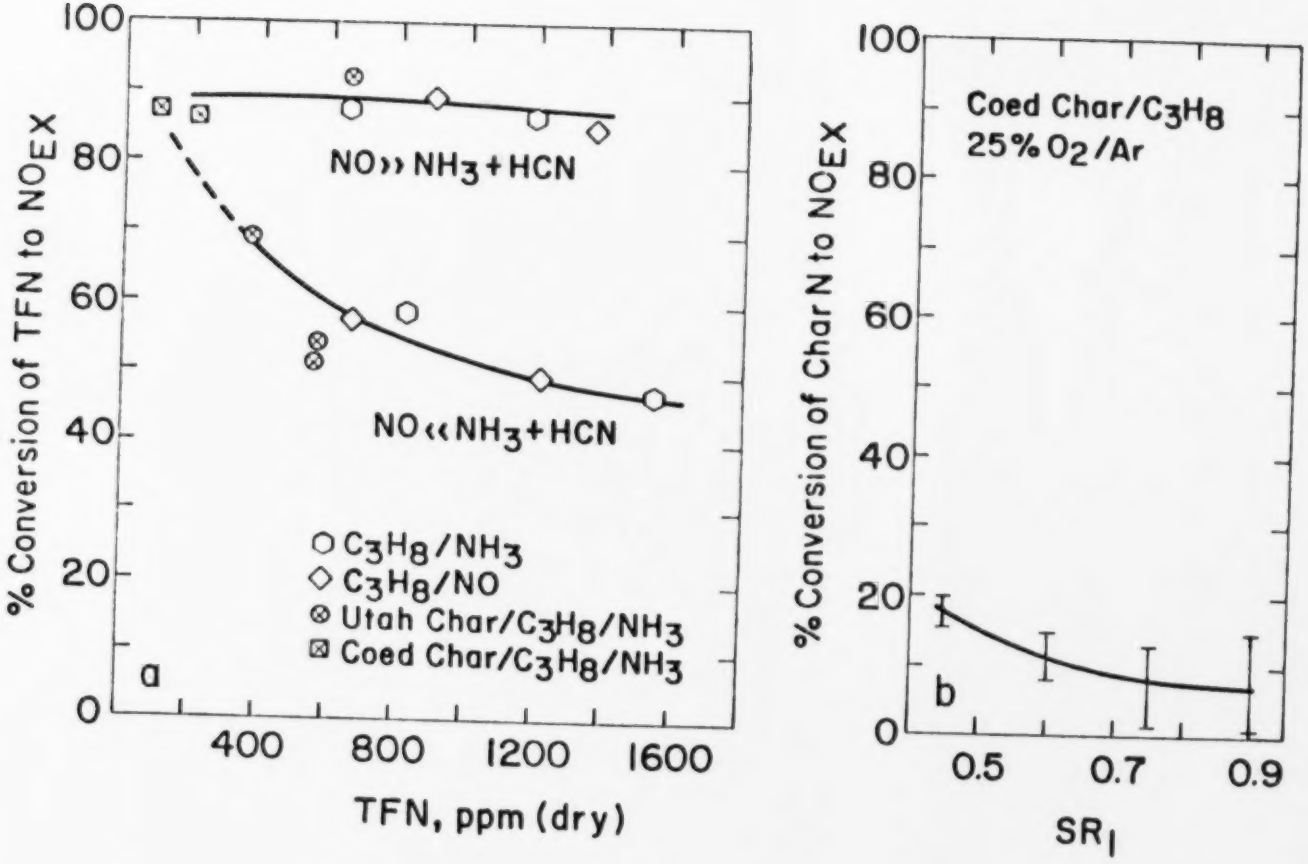
Figure	Captions
1	NO Emissions Under Excess Air and Staged Combustion Conditions as a Function of Coal Nitrogen Content
2	Correlation of NO Emissions with Coal Nitrogen Content, Pyrolysis HCN Yield, and Non-Volatile Nitrogen Content
3	Exhaust NO, XN, and Char N as a Function of SR_1
4	TFN Partition as a Function of Coal Rank
5	Second Stage Conversion of XN Species and Char N
6	Predicted Conversion of XN and Char N to NO
7	The Impact of First Stage Heat Removal
8	Influence of Cooling on Second-Stage TFN Conversion
9	The Impact of Cooling for Low Rank Coals
10	The Impact of Cooling for High Volatile Bituminous Coals

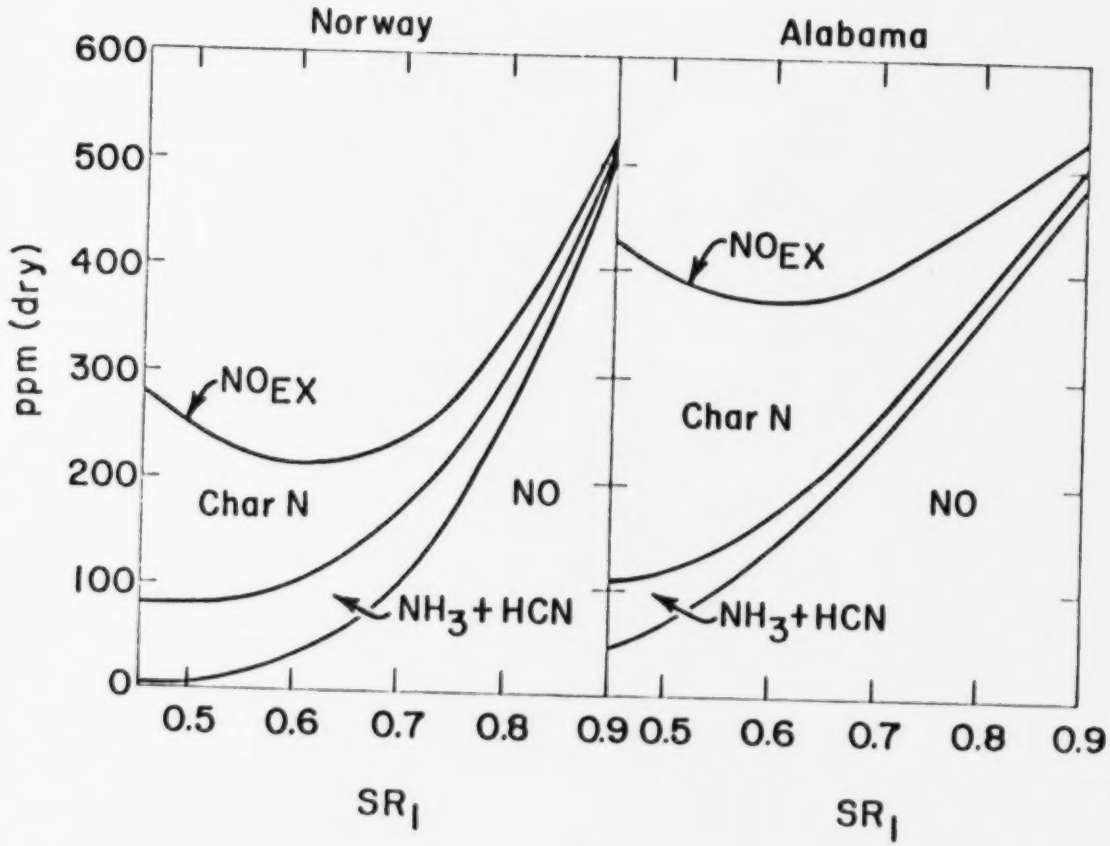

Excess Air
Staged
Norway
China
Canada
Fuel NO, ppm (Dry, 0% O2)
Min. NO, ppm (Dry, 0% O2)
% Fuel N (daf)
1600
1400
1200
1000
800
600
400
350
300
250
200
150
100
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5

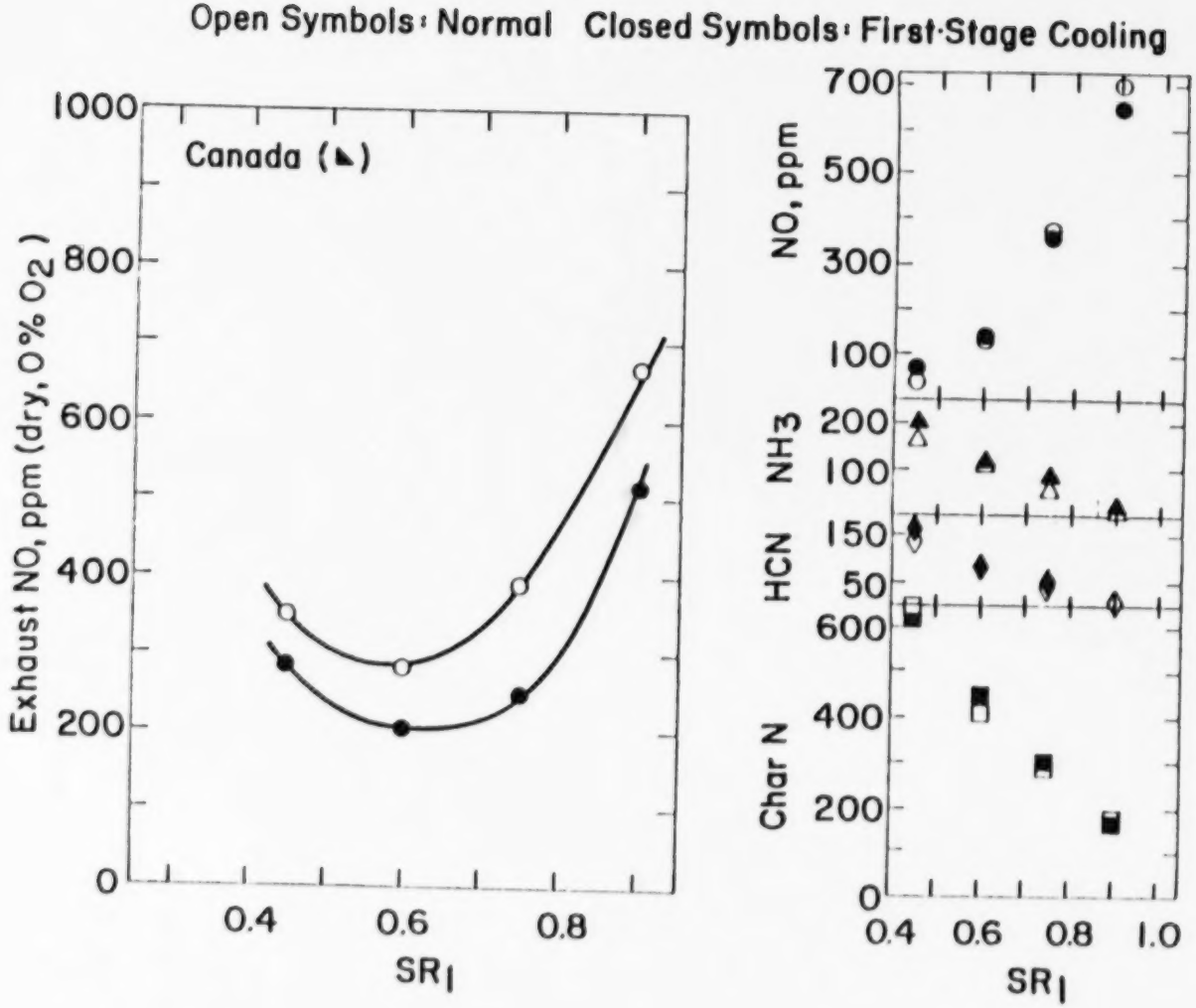

1400
1200
1000
800
600
400
200
0
NO (Measured), ppm
200 400 600 800 1000 1200 1400
NO(Calculated), ppm

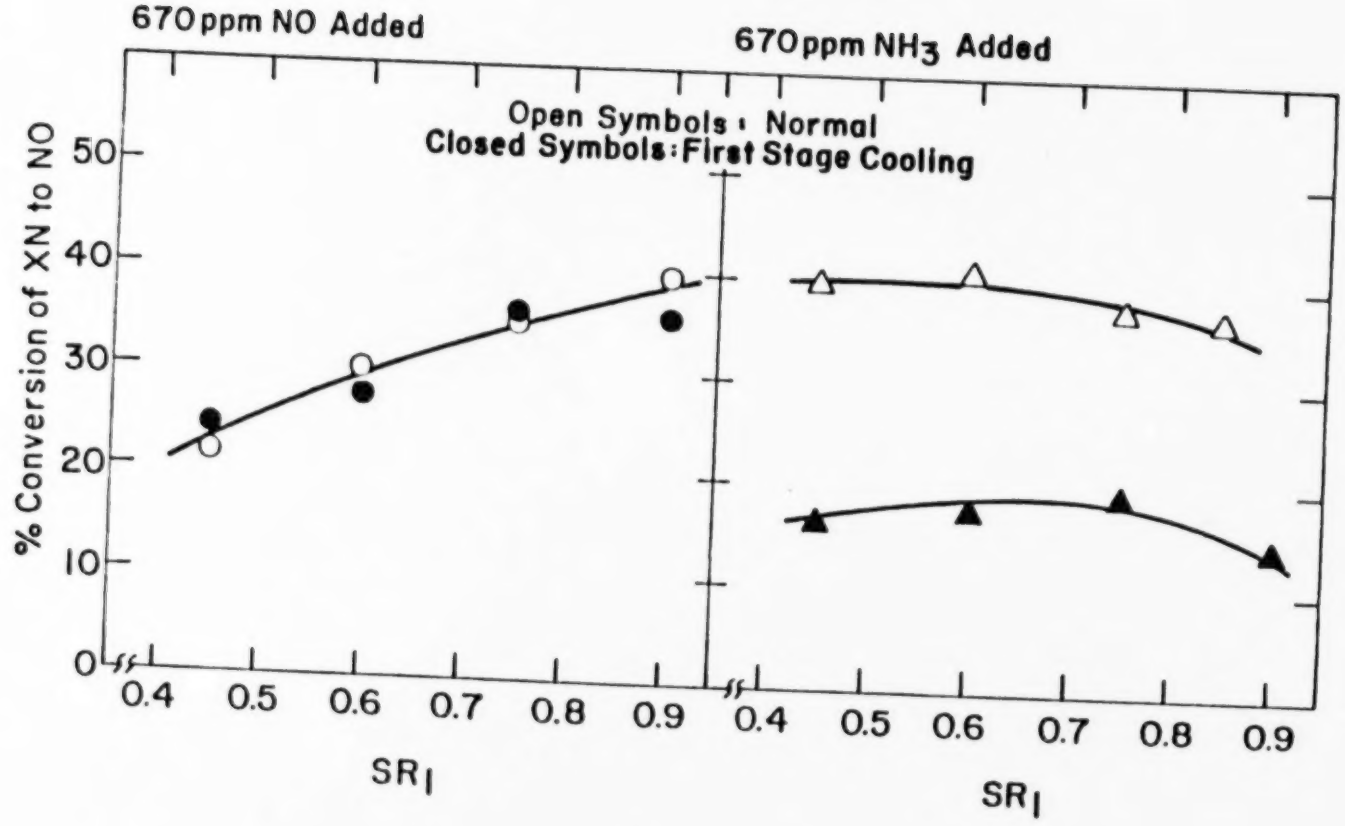

Utah (Bituminous, ○)
Canada (Lignite, ■)
Exhaust NO, ppm
400
200
XN, ppm
600
400
200
HCN
NO
NH3
NO
NH3
HCN
Char N, ppm
1200
800
400
0
0.5
0.7
0.9
SR1
0.5
0.7
0.9
SR1

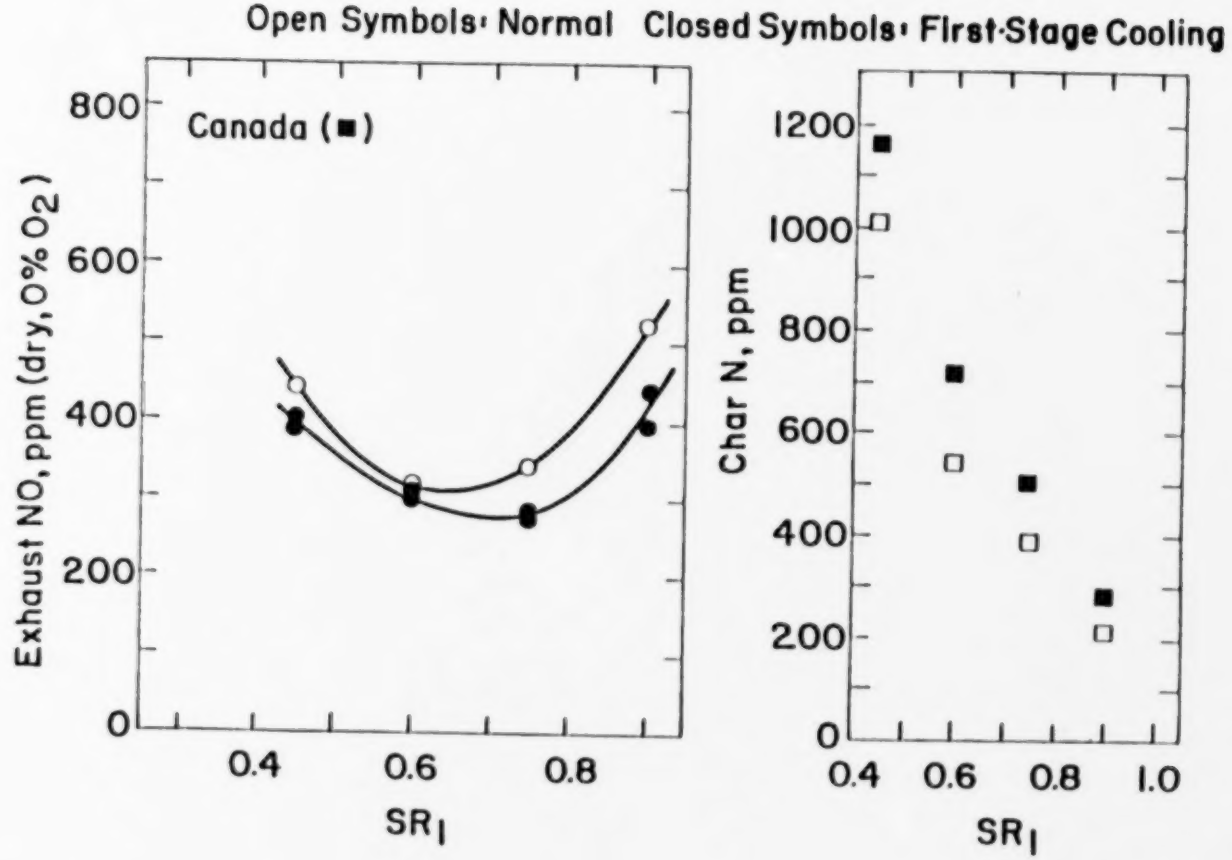

SR= 0.6
NH3
NO
HCN
% Initial Nitrogen
Low
Med.
A
B
C
High Volatile
A
B
C
A
B
Anthracite
Bituminous
Subbitum.
Lignite

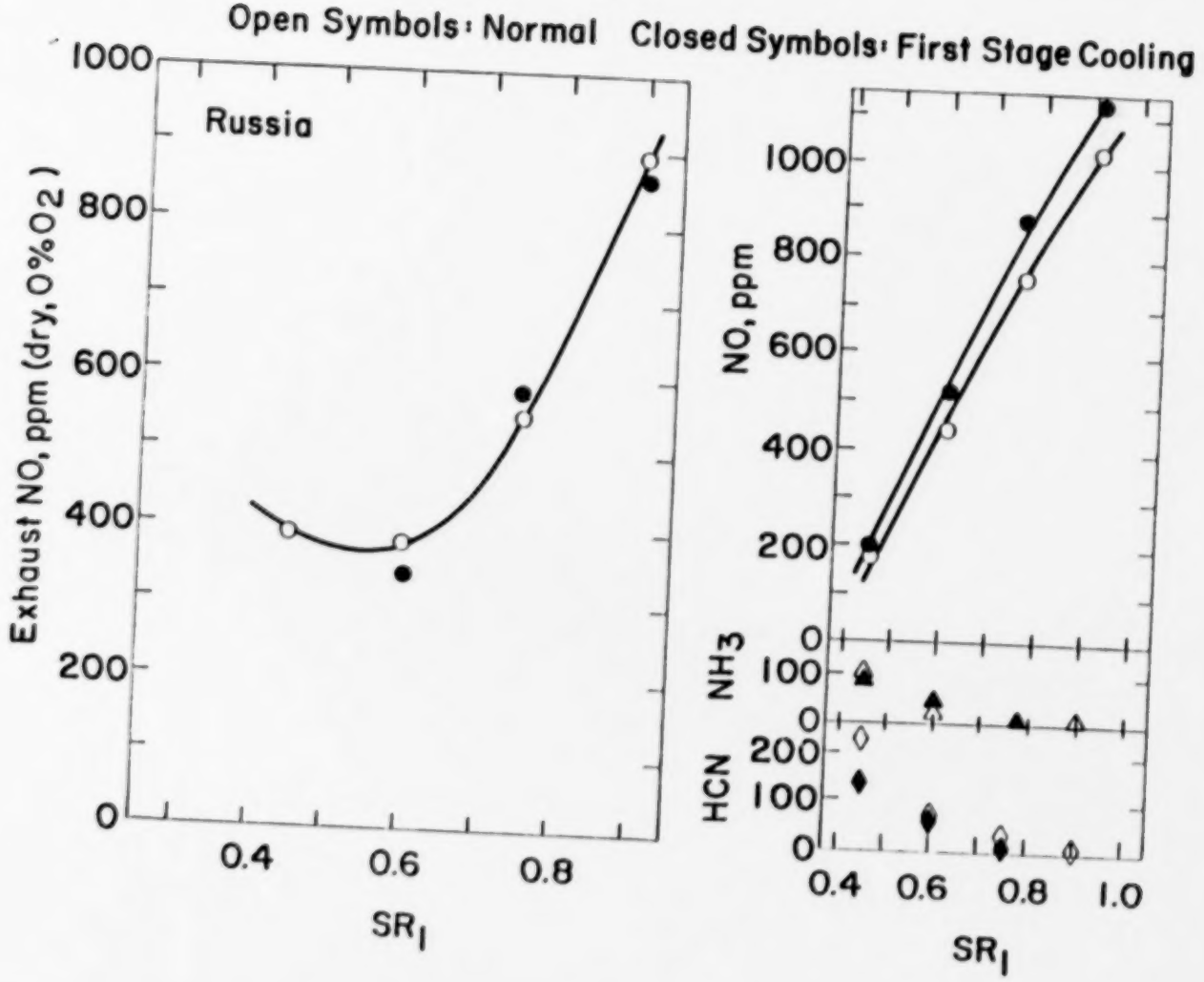

100
80
60
40
20
0
% Conversion of TFN to NOEX
NO›› NH3+HCN
NO‹‹ NH3+HCN
C3H8/NH3
C3H8/NO
Utah Char/C3H8/NH3
Coed Char/C3H8/NH3
a
400
800
1200
1600
TFN, ppm (dry)
% Conversion of Char N to NOEX
Coed Char/C3H8
25% O2/Ar
b
0.5
0.7
0.9
SR1


Norway
Alabama
600
500
400
300
200
100
0
ppm (dry)
NOEX
Char N
NO
NH3+HCN
0.5
0.6
0.7
0.8
0.9
SR1


Open Symbols: Normal Closed Symbols: First-Stage Cooling
Canada (◣)
Exhaust NO, ppm (dry, 0% O2)
1000
800
600
400
200
0
0.4
0.6
0.8
SR1
NO, ppm
700
500
300
100
NH3
200
100
HCN
150
50
Char N
600
400
200
0
0.4
0.6
0.8
1.0
SR1


670 ppm NO Added
670 ppm NH3 Added
Open Symbols : Normal
Closed Symbols: First Stage Cooling
% Conversion of XN to NO
0
10
20
30
40
50
0.4
0.5
0.6
0.7
0.8
0.9
SR1
SR1


Open Symbols: Normal Closed Symbols: First-Stage Cooling
Canada (■)
Exhaust NO, ppm (dry, 0% O_2)
800
600
400
200
0
0.4
0.6
0.8
SR_I
Char N, ppm
1200
1000
800
600
400
200
0
0.4
0.6
0.8
1.0
SR_I


Open Symbols: Normal Closed Symbols: First Stage Cooling
Russia
Exhaust NO, ppm (dry, 0% O2)
1000
800
600
400
200
0
0.4
0.6
0.8
SR1
NO, ppm
1000
800
600
400
200
0
NH3
100
0
HCN
200
100
0
0.4
0.6
0.8
1.0
SR1